Overview of Nano-Technology
Status and Opportunities

Robert Hull

Charles Henderson Professor of Engineering
Director, UVa NanoQuest Institute
University of Virginia

Richmond, August 4th, 2004

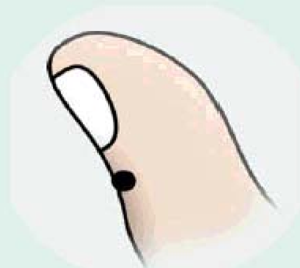
OUTLINE

- What is Nanotechnology and Why Now?
- Nanotechnology in the Present
- Future Challenges and Opportunities in Nanotechnology: Towards Broad-Based Nanomanufacturing
- Future Technological Horizons

What is Nano-Technology?

- The ability to engineer systems with components on length scales of 1 - 100 nm.
- Properties / structures are often different / better at such reduced scales
- If we make things smaller they are cheaper, lighter, use less power to operate, and we can have a lot more of them

Billions of nanometers
A two meter tall male is two billion nanometers tall.



A million nanometers
The pinhead sized patch of this thumb (circled in black) is a million nanometers across.

Thousands of nanometers
Biological cells, like these red blood cells, have diameters in the range of thousands of nanometers.

Nanometer
Ten shoulder-to-shoulder hydrogen atoms (blue balls) span 1 nanometer. DNA molecules are about 2.5 nanometers wide.

Less than a nanometer
Individual atoms are up to a few angstroms, or up to a few tenths of a nanometer, in diameter.

Why now?

- **Confluence of critical capabilities in nano-science:**
  - Computational methods
  - Fabrication and synthesis methods
  - Measurement methods
  - Improved understanding of nanoscale biological processes
- **New materials and phenomena**
  - High surface / volume ratio – "old" materials with new properties dominated by surfaces, interfaces
  - Entirely new nanostructured forms of materials
  - New phenomena in quantum regime
  - Control of fundamental units of light, electricity, magnetism
- **Existence proofs of enabling impacts upon industries with tens to hundreds of billion dollar annual sales…**
  - Micro- (Nano-)Electronics
  - Read-write heads on hard drives
  - Catalysis of chemical reactions

And Money Helps!

The National Nanotechnology Initiative

Agency	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004*
DOC	8	18	38	69	62
DOD	70	110	180	243	222
DOE	58	94	91	133	197
NASA	5	20	46	33	31
NIH	32	36	41	65	70
NSF	97	150	199	221	247
TOTAL	270	428	595	774	847

Units: $ million

The National Nanotechnology Initiative

- **NNI Nine "Grand Challenges"**
  - Nanomaterials by Design: *Stronger, Lighter, Harder…*
  - Nano-electronics, -optics and -magnetics
  - Healthcare: *Drug delivery, biosensors, biocompatibility…*
  - Environment: *Particulate removal, catalytic supports*
  - Energy: *Storage and conversion, solar cells, thermoelectrics*
  - Microspacecraft: *Light weight, high T coatings; self repair*
  - Bio-threat detection: *Weapons, HIV, tuberculosis…*
  - Transportation: *Lighter and safer….*
  - National Security: *Nanoelectronics, structural mats, failure*
- **Currently Being Updated for the Next Decade**

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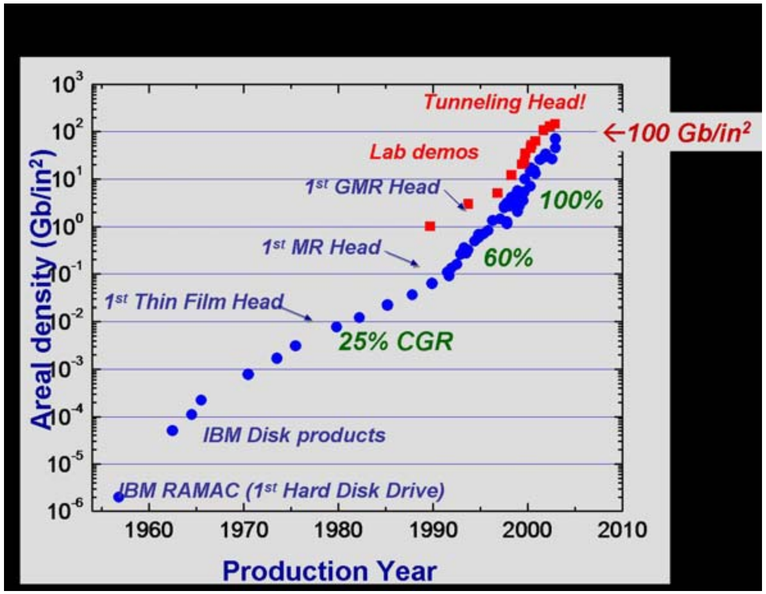
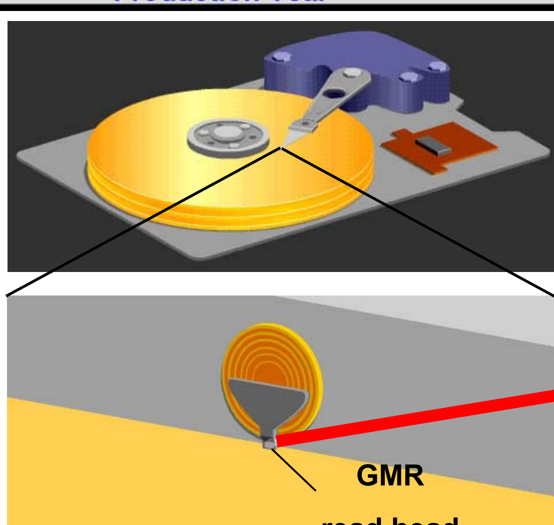
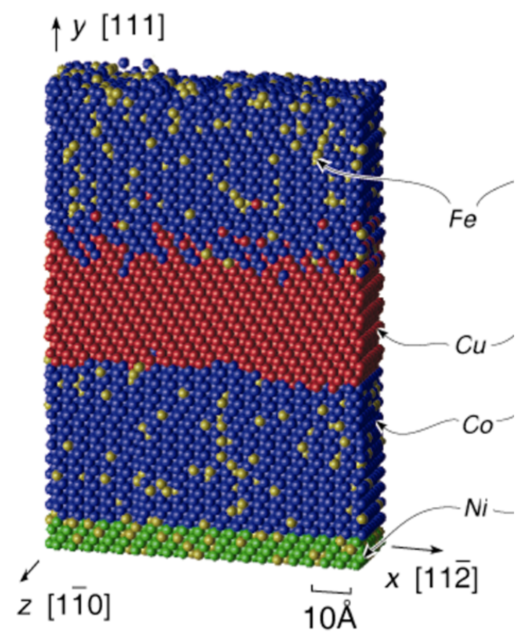
Existing Major Achievements of Nanotechnology

I. GMR Read-Write Heads



Top left: Evolution of hard drive storage capacity vs. year first in production (image courtesy S. Parkin, IBM); Bottom left: Schematic image of a magnetic disc drive; Bottom right: Atomistic simulations of a giant magnetoresistive layer structure (image courtesy H. Wadley, U. Virginia)

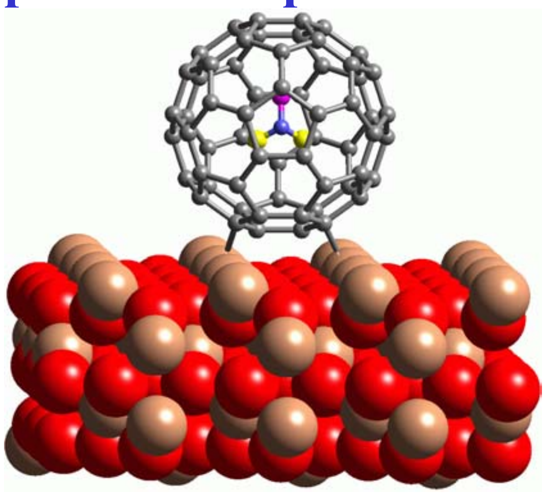




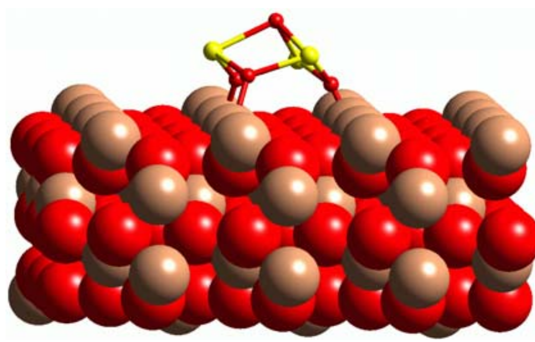
Existing Major Achievements of Nanotechnology

II. – Nanostructured Catalysts

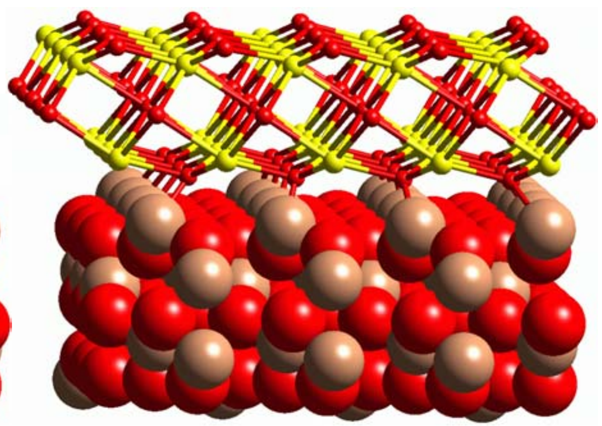
Research in the chemical industry into new catalyst materials with nm sized pores has captured a market of tens of billions of dollars per year.



$La_2CeN@C_{80}$ on Al_2O_3

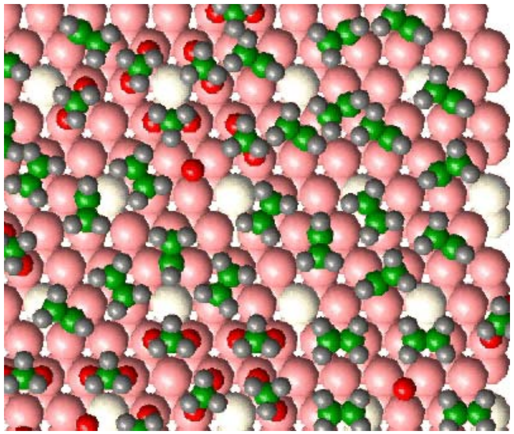


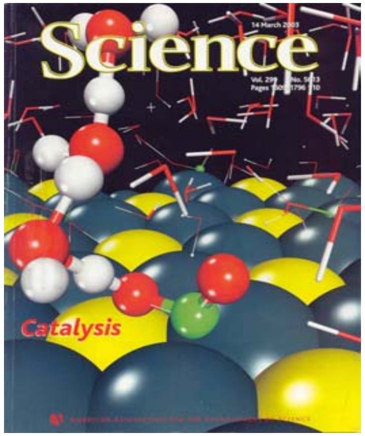
La_3O_4 cluster on Al_2O_3



La_2O_3 surface on Al_2O_3

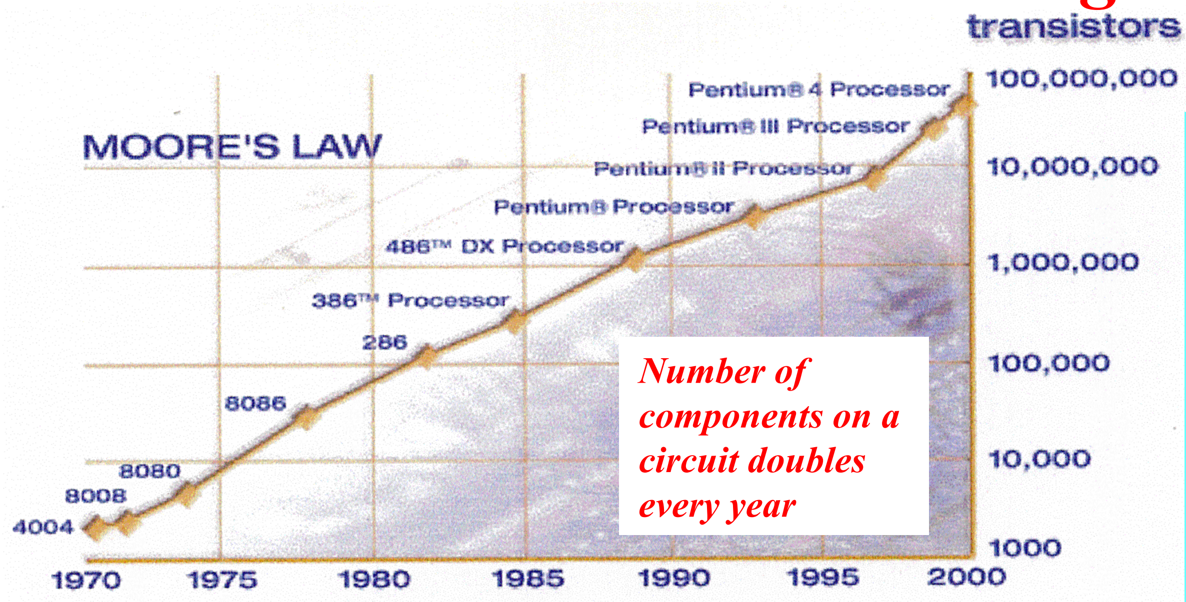
Use of endohedral metallofullerenes as catalyst precursors for molecular clusters and extended surfaces (Dorn,VT; Tissue, VT; RJ Davis, UVA; Neurock, UVA)





Existing Major Achievements of Nanotechnology

III. Electronics – Scaling to the Nanoscale

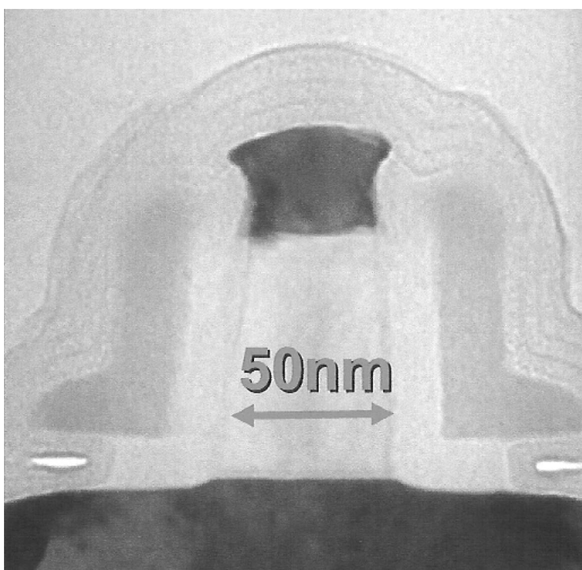


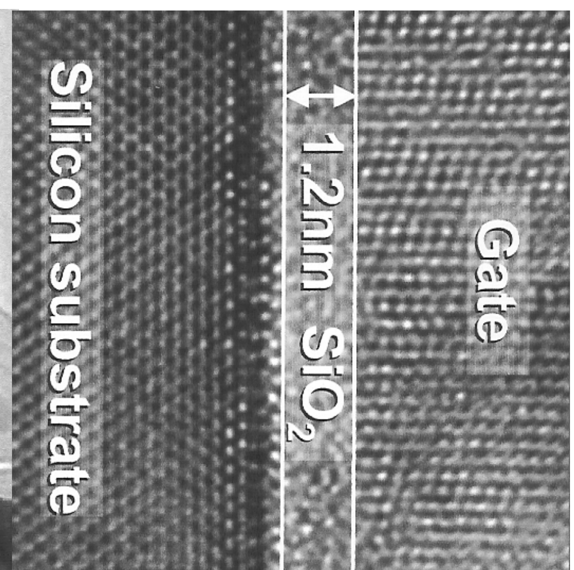
> 100, 000, 000,000 devices per 30 cm wafer

Minimum dimensions < 100 nm lateral, ~ 1 nm vertical

Cost to the consumer 0.0000001 c each

A $200+ billion / year industry





Moore's Law: An Analogy

- ***If the aircraft industry had evolved at the same rate as the microelectronics industry in the last 25 years, a Boeing 777 today would cost $500, and circle the globe in 20 minutes on 5 gallons of fuel.***

So What Else Might Be Possible?

Existing Major Achievements of Nanotechnology

- **Other existing applications include:**
  - *High performance sports equipment*
  - *Specialized auto / aero components*
  - *Polishing powders and slurries (CMP)*
  - *Stain-free fabrics*
  - *Sun tan lotion and cosmetics*
  - *Selective optical coatings (photographic film etc.)*
  - *Telecommunications components*
  - *Machine tools*
  - *Corrosion and scratch resistant paints / coatings*

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NNI Grand Challenge Workshop on Nanomaterials

Arlington, Virginia 11-13 June 2003

Chairs: R. Hull, UVa; L. Haworth, NSF

Proposed New Grand Challenge

NanoFoundries: ***Development of Techniques, Methods and Instruments for the Fabrication of Nanoscaled Materials and Systems that Enable Economically Viable Applications of Broad Benefit to Industry, Technology, the Economy, the Environment, Health, and Society***

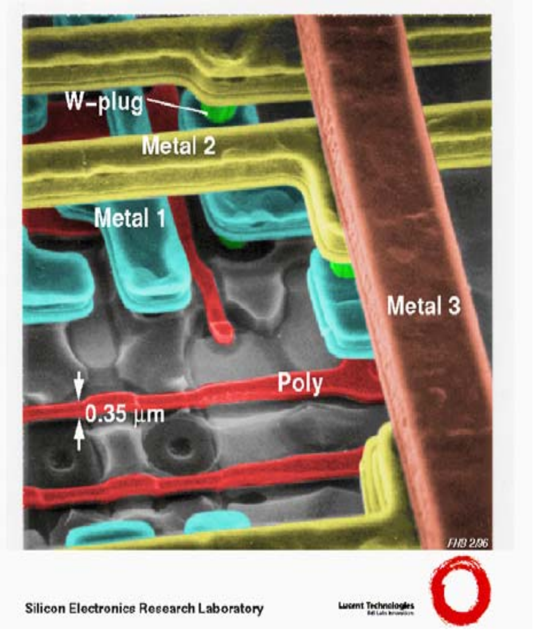
Routes to Commercial NanoManufacturing - I

Low material volume, high precision systems

- E.g. engineered vol. in micro-electronic circuit (>10^8 components) is c. 1 mm^3

- Basic material cost not a key issue

- Fundamental needs – Increasing demands on lithographic precision, cost; Development of new materials technologies

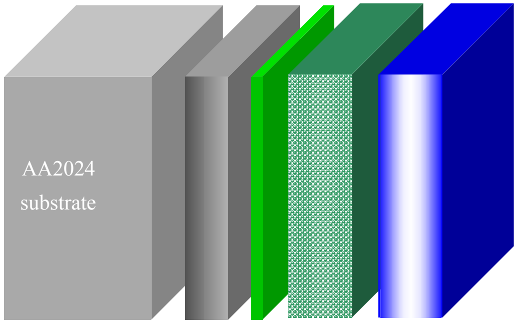


Nanostructured functional coatings

- E.g. 1 µm thick coating on an airplane wing requires volume of c. 100 cm^3

- Challenges in uniform coating of complex surfaces

- Fundamental needs – self interrogation / repair for failure; sensing; internal communications; application methods



UVa-AFOSR MURI on "Multi-Functional Aerospace Coatings"

Internally structured / nanocomposite systems

- Porous materials, e.g. aerogel, internal surface areas of 1000 m^2 per g – air or intercalate.

- Unique thermal, electrical, acoustic, dielectric….properties

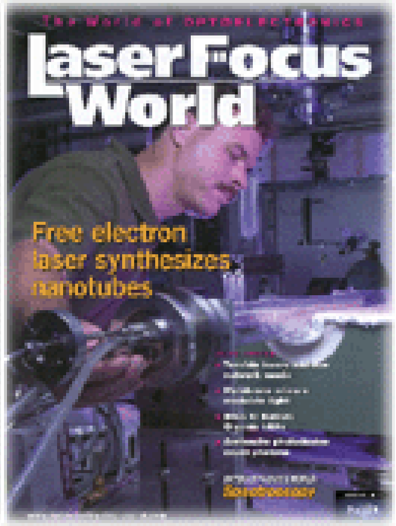
- More generally, nanocomposite materials can greatly enhance properties (e.g. strength) with small fraction of "filler".

http://eande.lbl.gov/ECS/Aerogels/saphoto.htm

- Still requires significant volumes of minority phase material(s); optimize properties per volume required: simulation, understanding.

Scaling of synthesis methods

- Key to multiple macroscopic applications (mechanical components, transportation, civil infrastructure,environmental etc.)



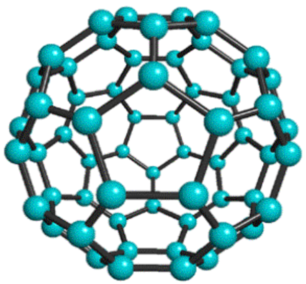
- Just make more!

Implementing the Grand Challenge

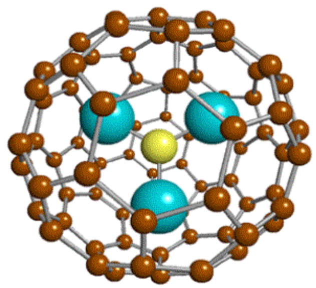
- ***Discovery*** of new materials and properties, and ***invention*** of new techniques, instruments
- New techniques for synthesizing and refining ***nano-materials in large quantities.***
- New methods for ***self-assembly*** of materials, based upon both biological and non-biological methods.
- Controlled ***hierarchical structures*** with multiple length scales down to the nano-scale
- Materials, methods, and instruments for ***harnessing sub-atomic properties*** e.g. electron spin and quantum interactions.
- Improved instruments and techniques for ***structuring and patterning*** materials at ever-increasing levels of precision.
- The ability to measure 3D structure, properties, and chemistry of materials down to the atomic scale – a ***"nano-GPS"***.
- The development of ***computational methods, algorithms, and systems*** – both classical and quantum – to enable realistic simulation over all relevant length and time-scales.
- The ***interface between nanomaterials and biological systems*** – enabling widespread improvements in human health.

JCOTS Nanotechnology Advisory Committee

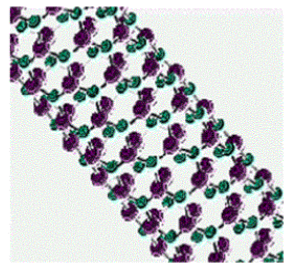
Discovery **of new materials and properties, and *invention* of new techniques and instruments**



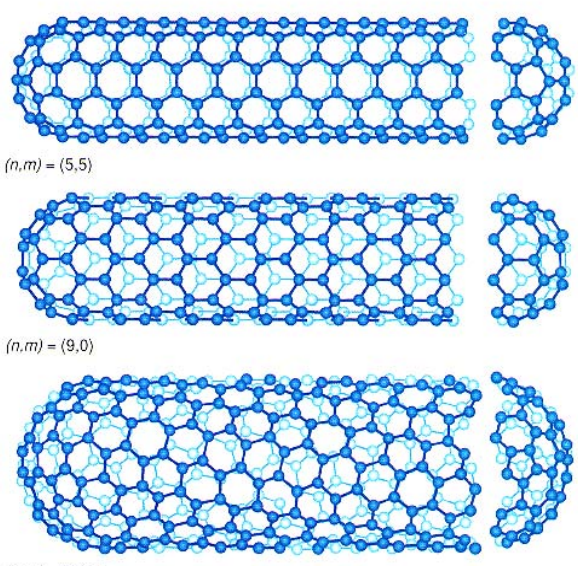
C_{60} Fullerene



$Sc_3N@C_{80}$ Metallofullerene



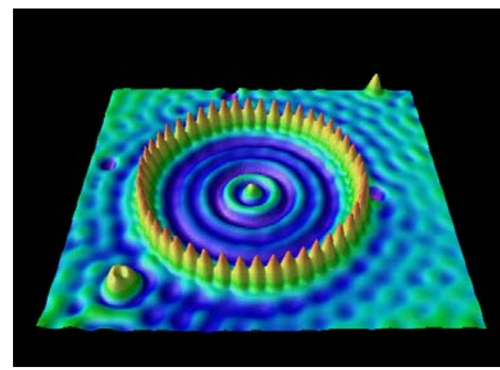
Carbon Nanotube



(n,m) = (5,5)
metal

(n,m) = (9,0)
semimetal

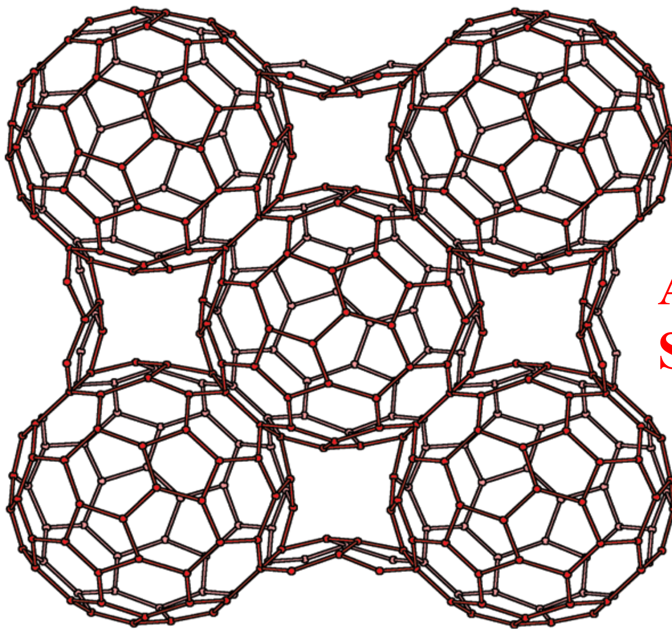
(n,m) = (10,0)
semiconductor

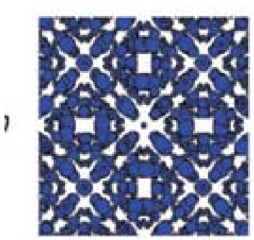


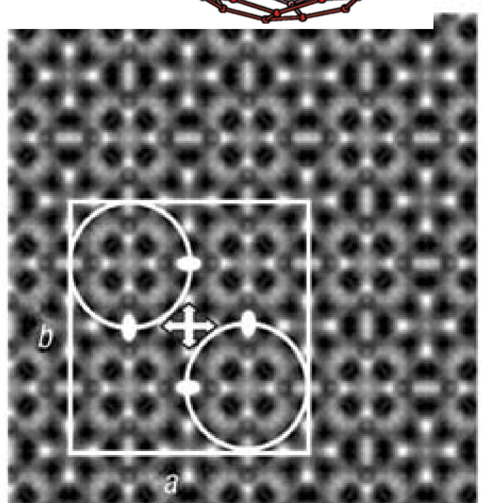
Eigler et al, IBM

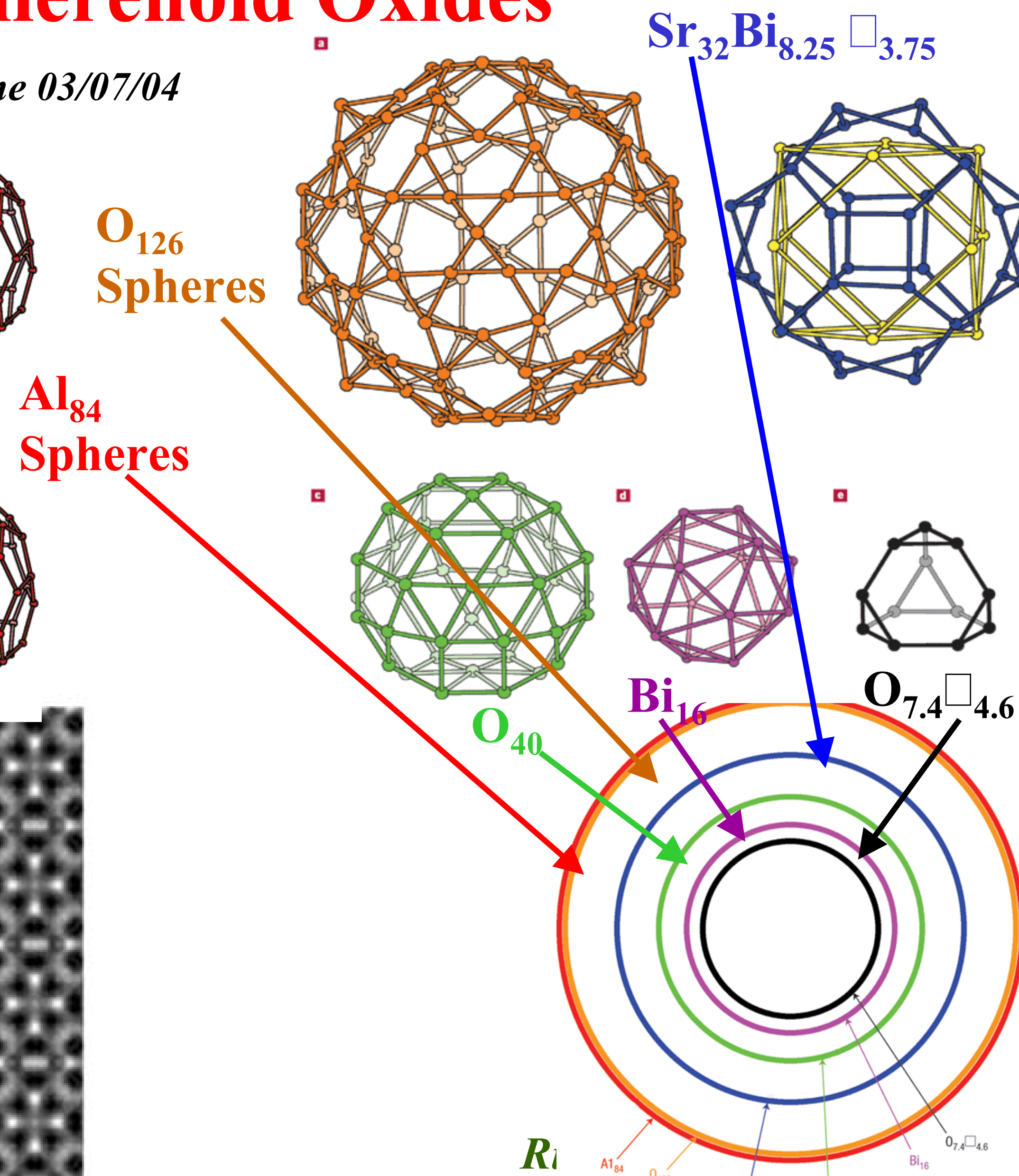
New Fullerenoid Oxides

Hervieu et al, Nature Materials, Online 03/07/04









R

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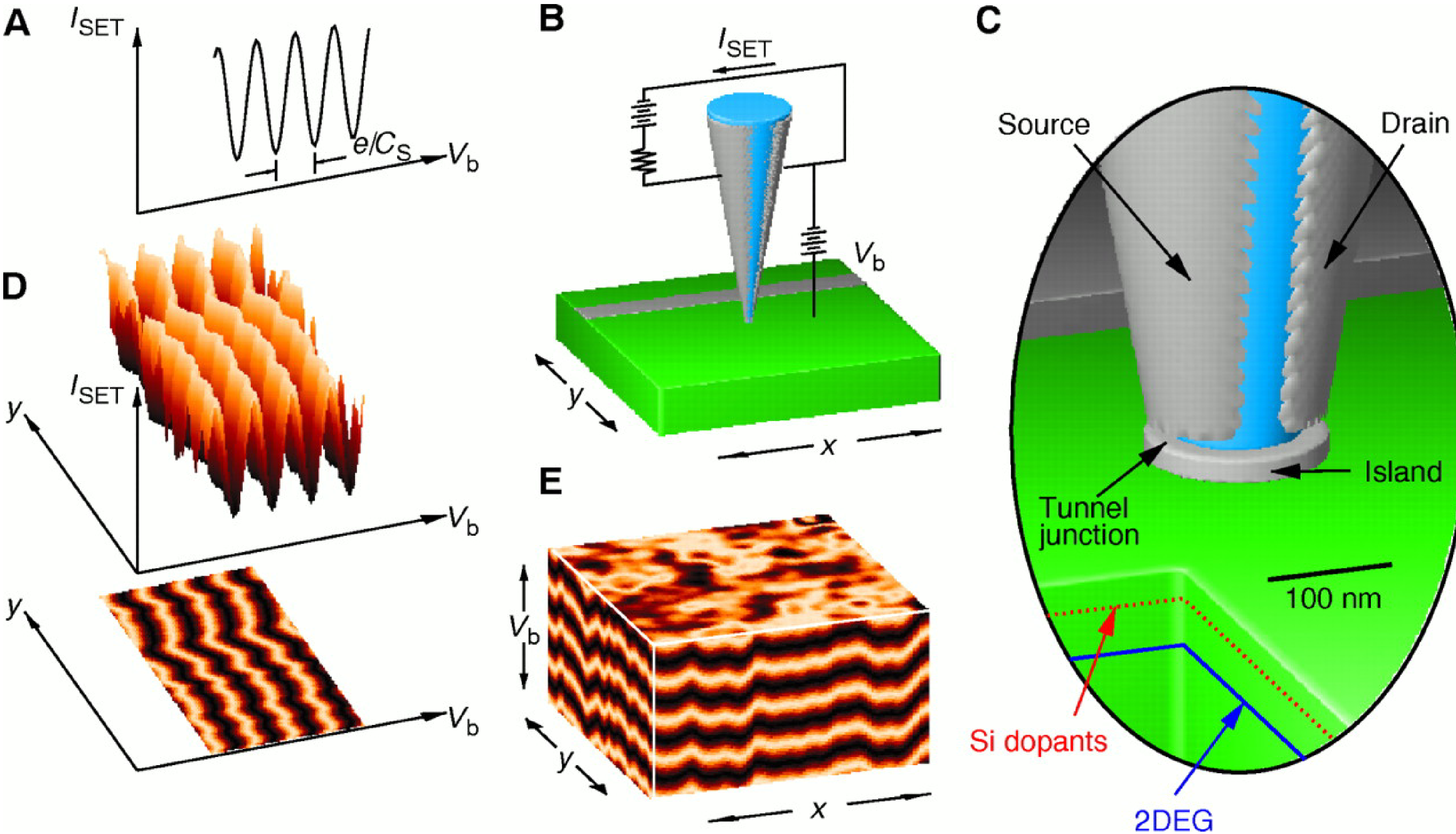
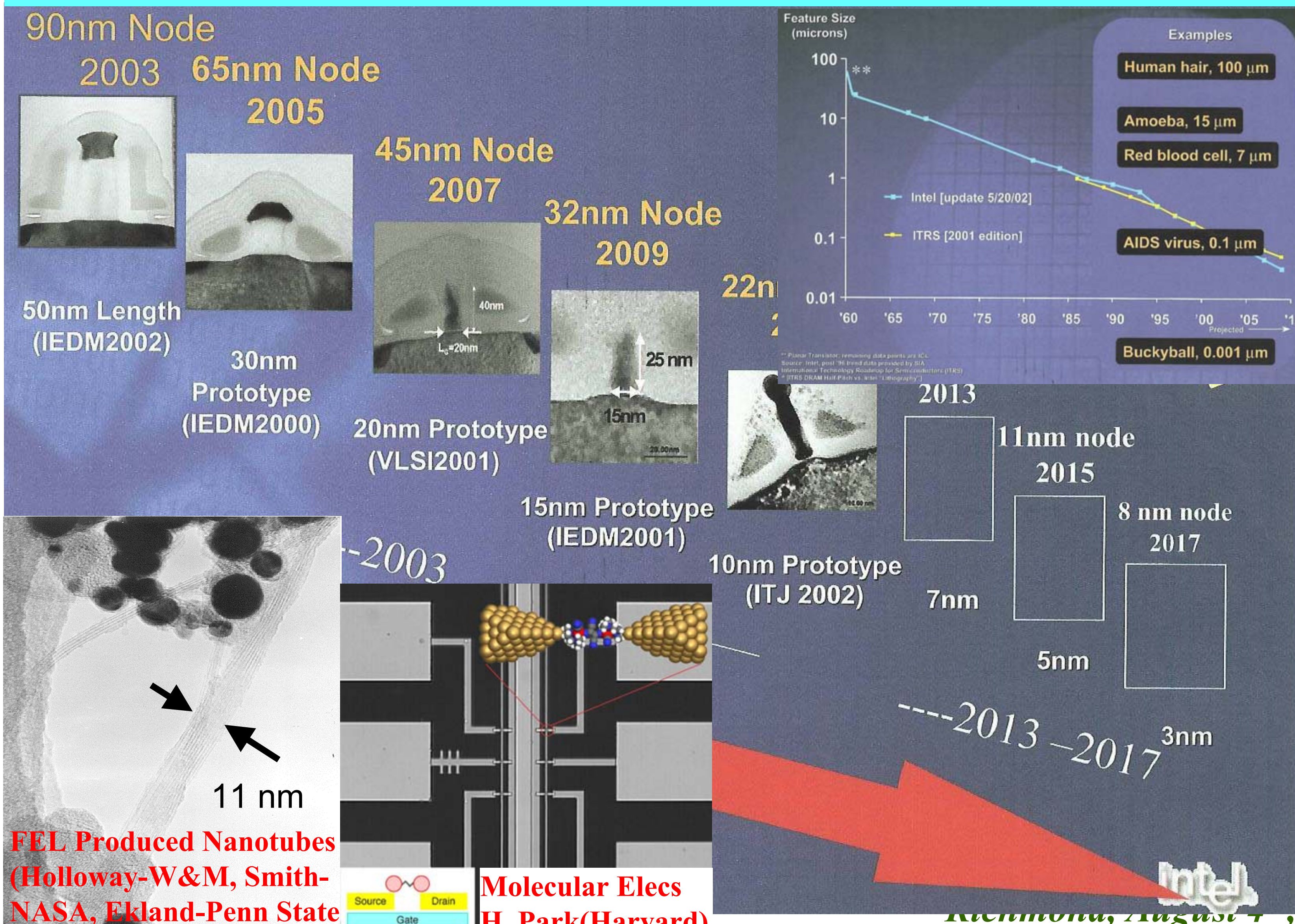
Single Electron Transistor Charge Microscopy



Spatial resolution ~ 100 nm, charge sensitivity ~ 0.01 e

Yoo et al, Science 276, 579

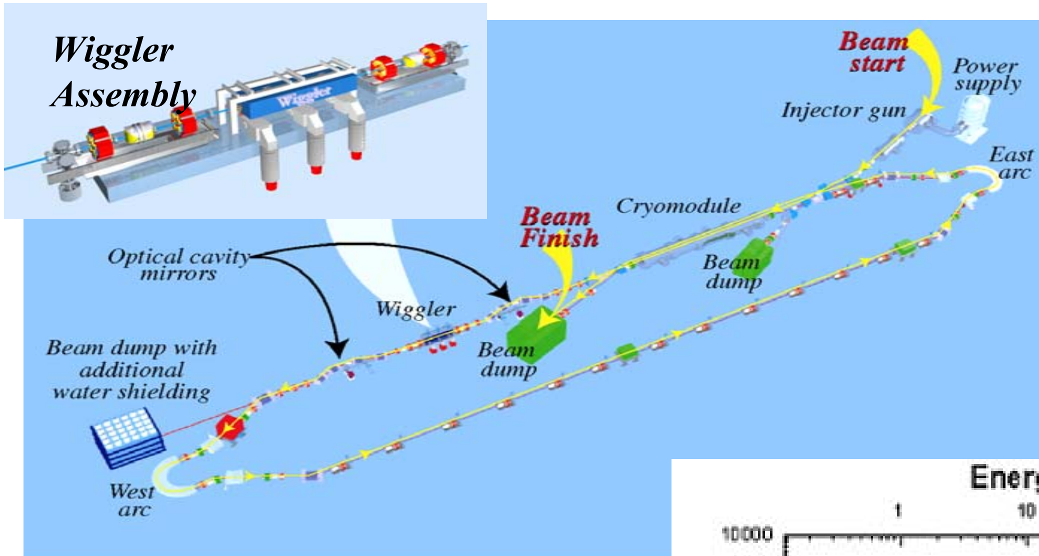
New techniques for synthesizing and refining *nano-materials in large quantities*



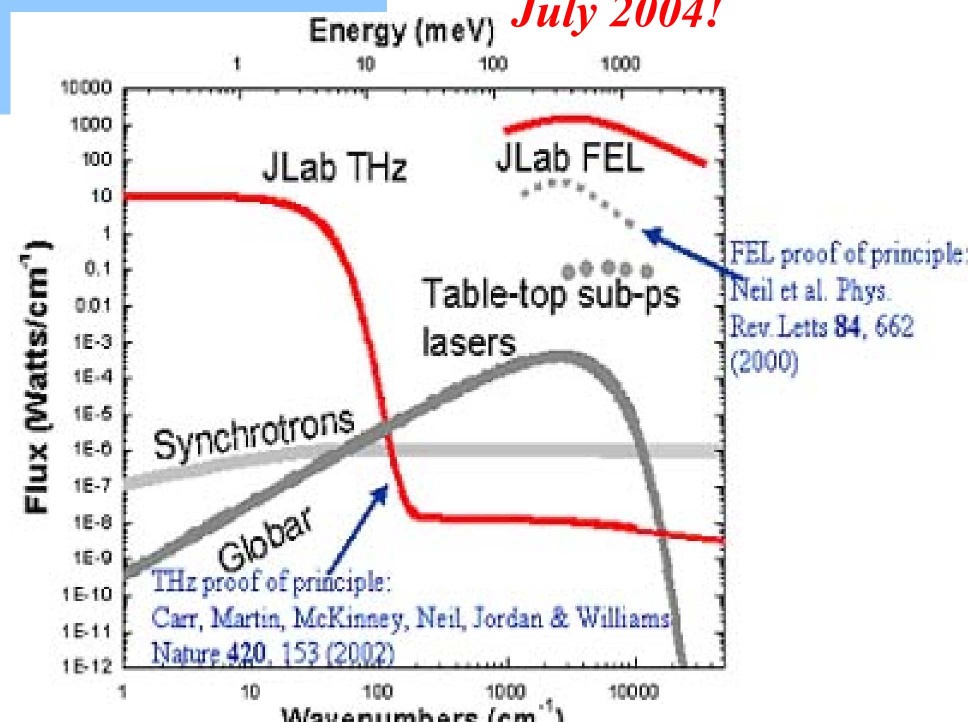
FEL Produced Nanotubes (Holloway-W&M, Smith-NASA, Ekland-Penn State

Molecular Elecs H. Park(Harvard)

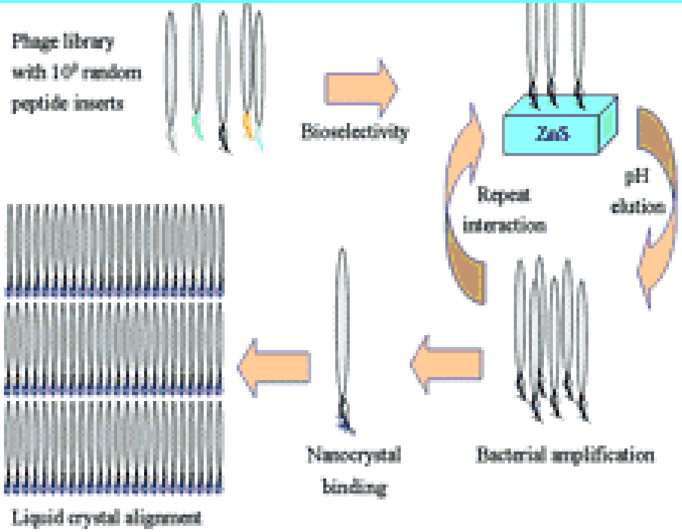
Jefferson Labs Free Electron Laser

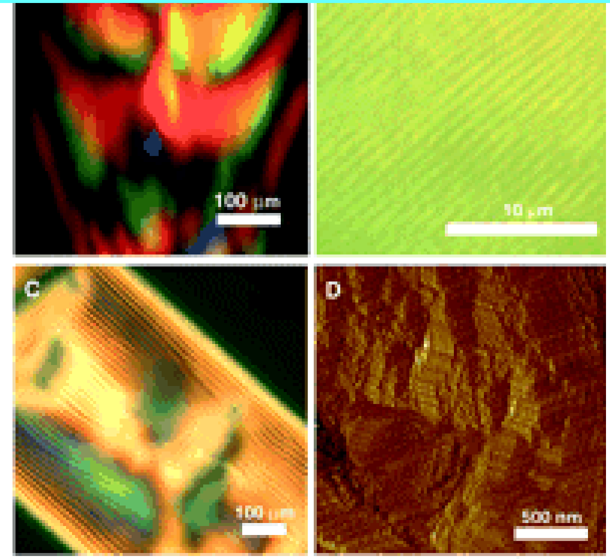


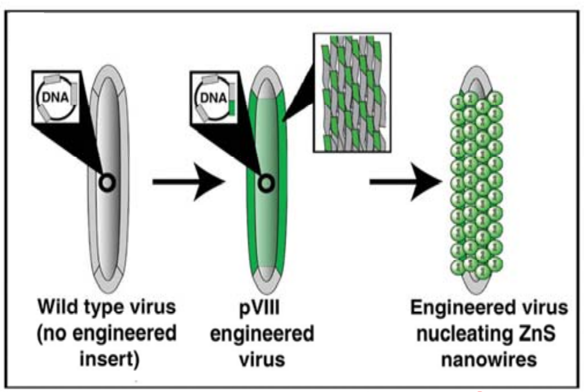
10 kW demonstrated July 2004!



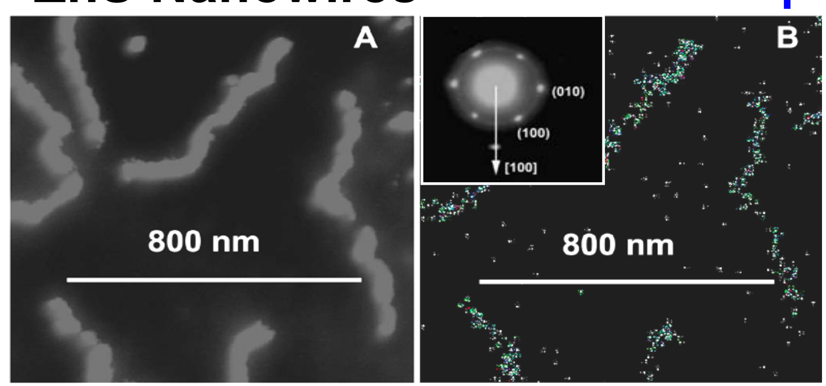
New methods for *self-assembly* of materials, based upon both biological and non-biological methods







ZnS Nanowires **Zn map**



Viral Mediated Assembly of Nanowires and Ordered QD Arrays

Belcher group, MIT. Science 296, 892 (2002); Proc. Nat. Acad. Sci. 100, 6946 (2003).

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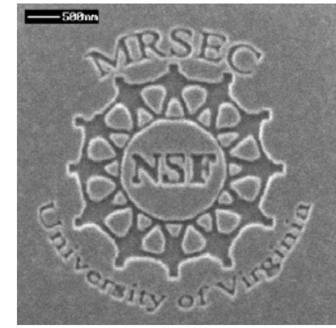
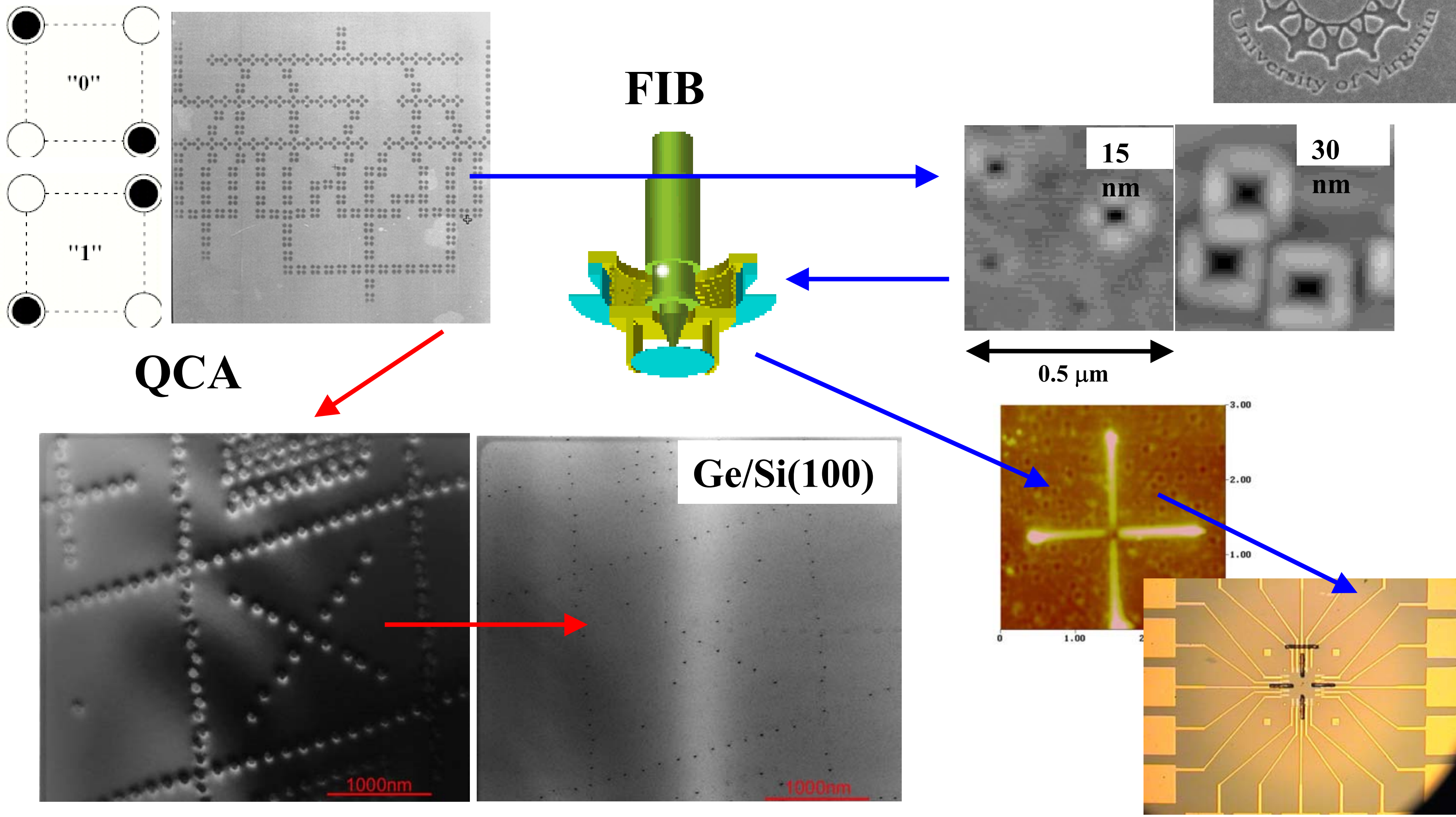
UVa Materials Research Science and Engineering Center

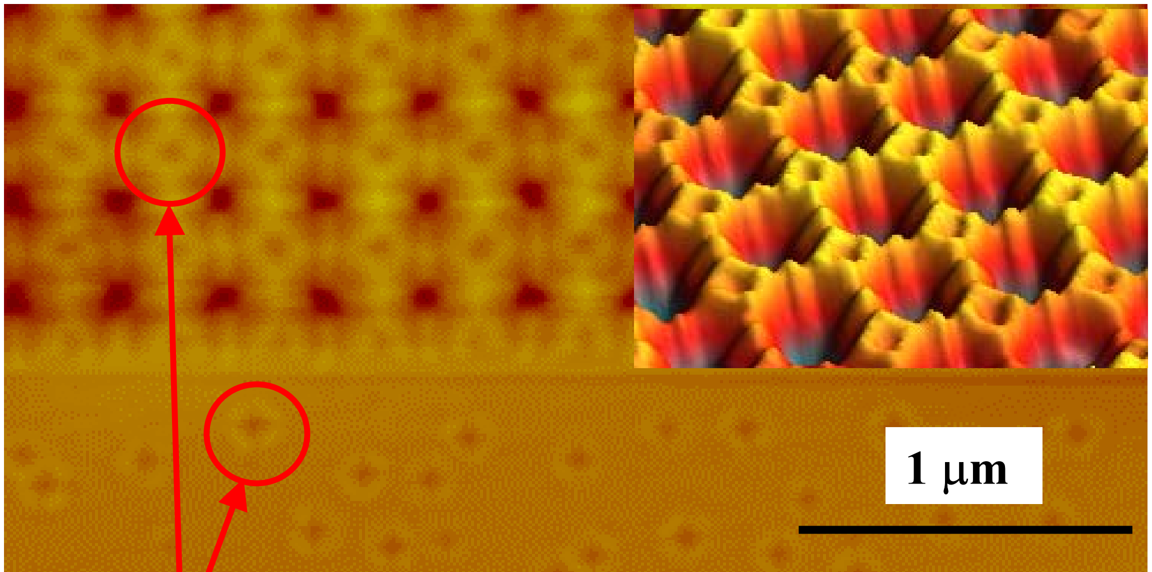
The Center for Nanoscopic Materials Design

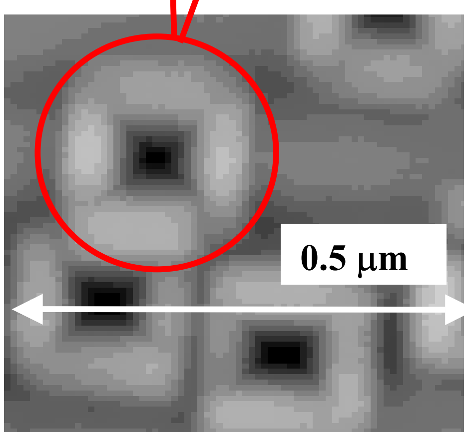




Richmond, August 4th, 2004

Controlled ***hierarchical structures*** with multiple length scales down to the nano-scale



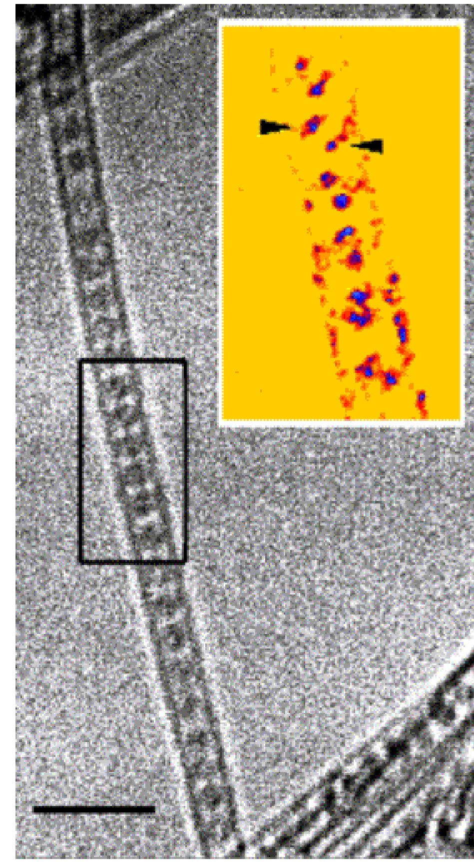


Quantum Dot Molecules

Hierarchical Assembly of Semiconductor Nanostrutures

J.Gray, S. Atha, and R. Hull, University of Virginia

J. Floro, Sandia National Laboratories



Peapod Fullerenes

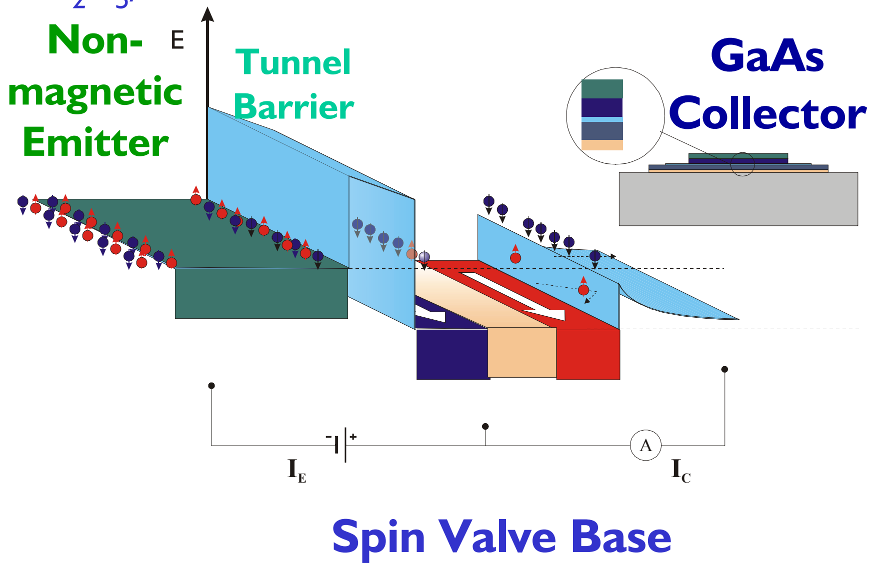
D. Luzzi et al, U. Penn.

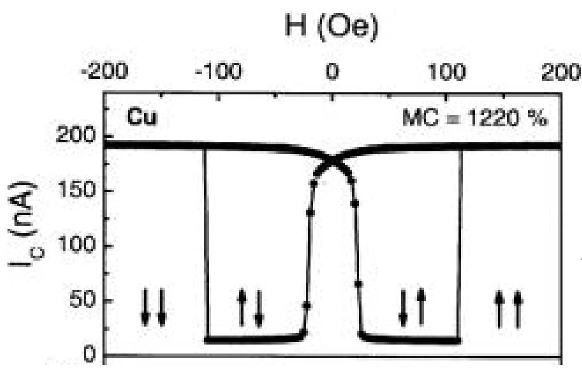
E.g. Chem Phys. Lett. 315, 31; 321, 169

Materials, methods, and instruments for ***harnessing sub-atomic properties*** e.g. electron spin and quantum interactions

Three terminal magnetic tunnel transistor

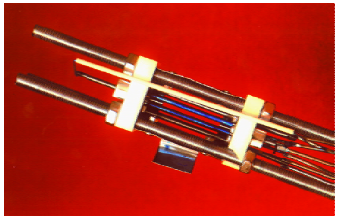
GaAs(001)/5 nm $Co_{70}Fe_{30}$/4 nm Cu/5 nm $Ni_{81}Fe_{19}$/ 1.8 nm Al_2O_3/30 nm Au

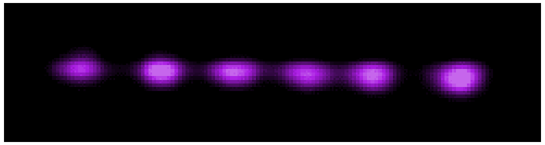




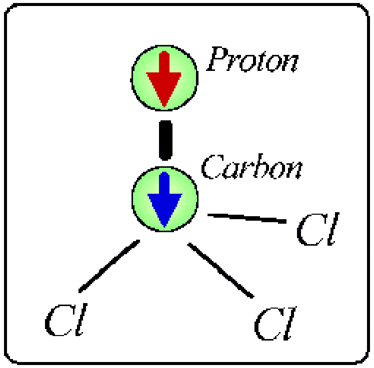
Van Dijken, Jiang and Parkin Appl. Phys. Lett. 82, 775 (2003)

Quantum Computing





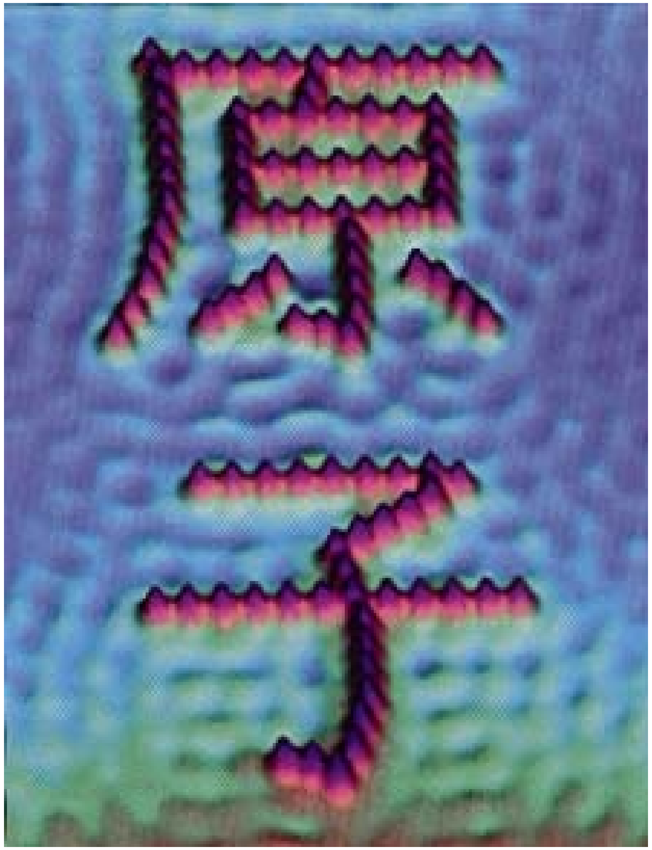
Ion Trap Quantum Computing



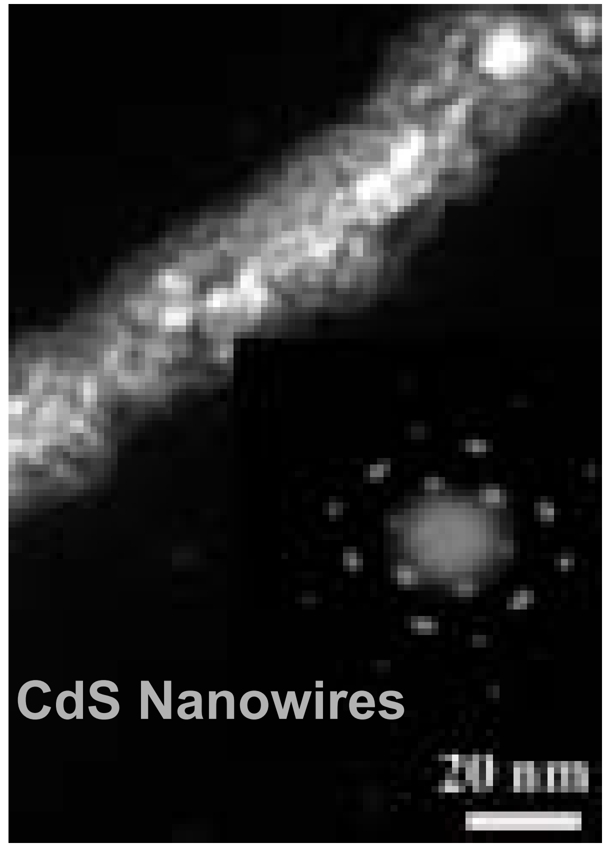
NMR Based Algorithms

www.qubit.org *(U.Oxford)*

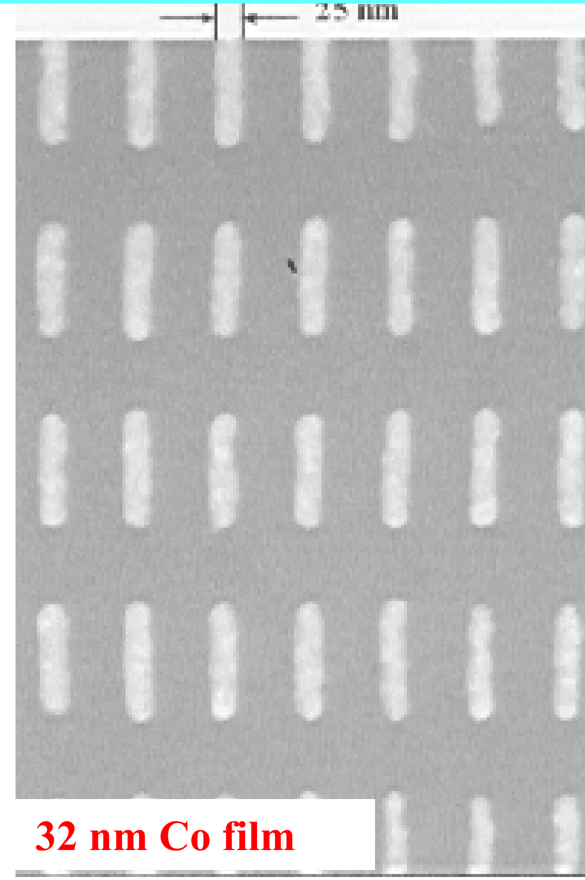
Improved instruments and techniques for ***structuring and patterning*** materials at ever-increasing levels of precision



STM Atomic Manipulation
Eigler group, IBM



Viral Assembly **Mao, Belcher et.al. e.g. *Proc. Nat. Acad. Sci.* 100, 6946.**



Nano-Imprinting
Chou group, Princeton
JVST B**16**, 3825 (1998)

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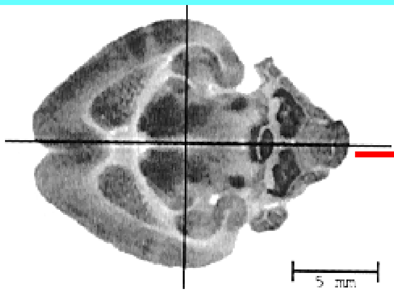
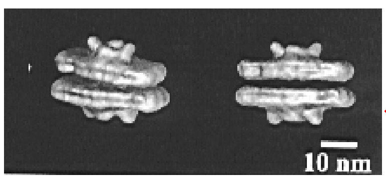
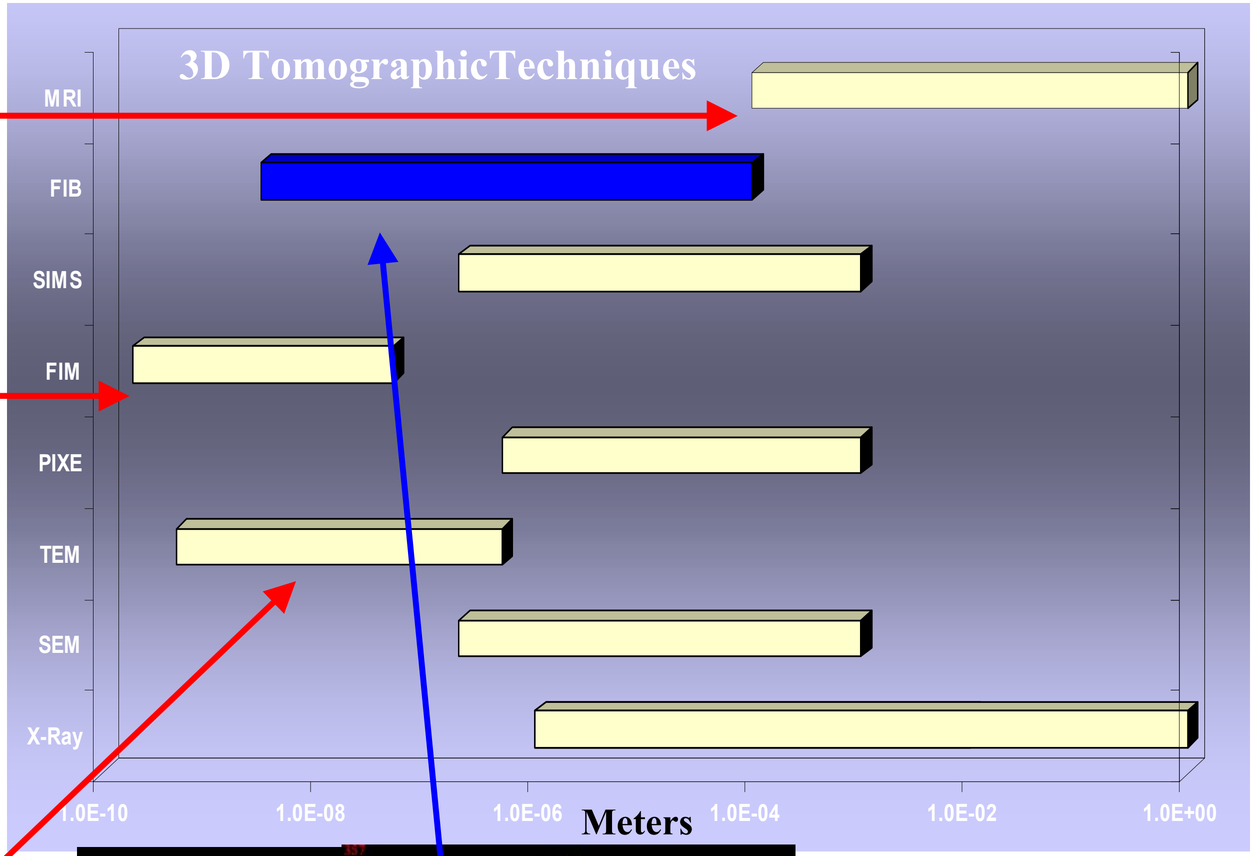
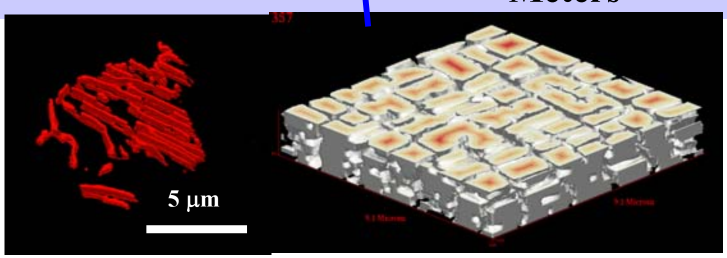
The ability to measure 3D structure, properties, and chemistry of materials down to the atomic scale – a ***"nano-GPS"***.



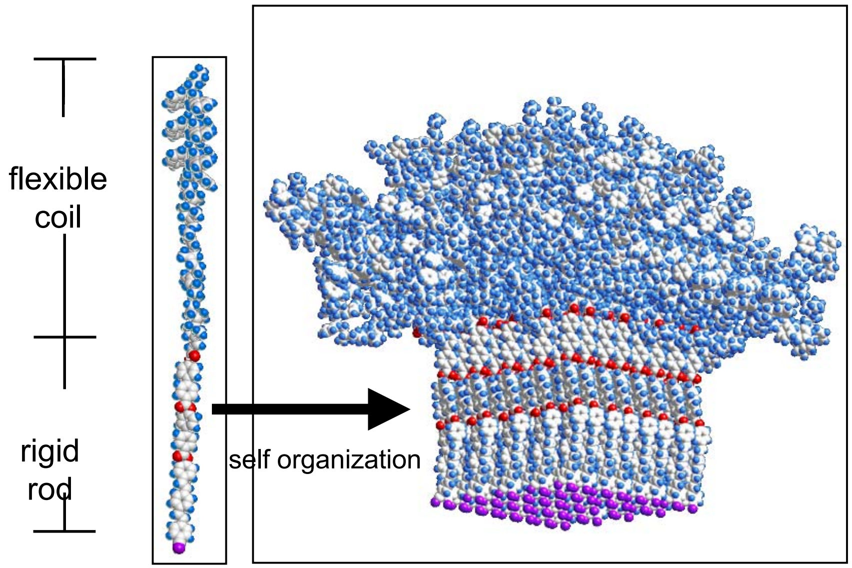




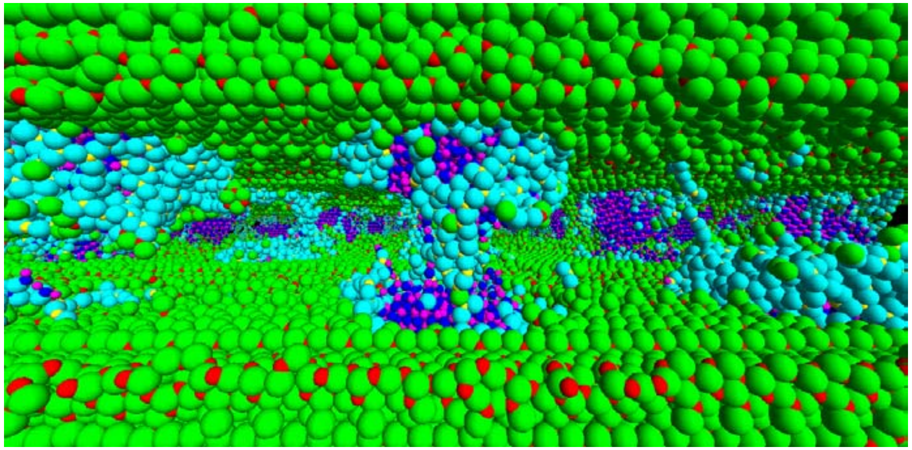


Richmond, August 4th, 2004

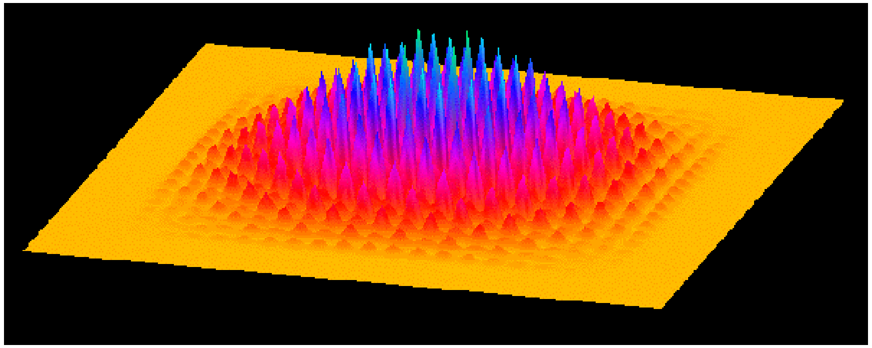
Development of ***computational methods, algorithms, and systems*** to enable realistic simulation over all relevant length and time-scales.



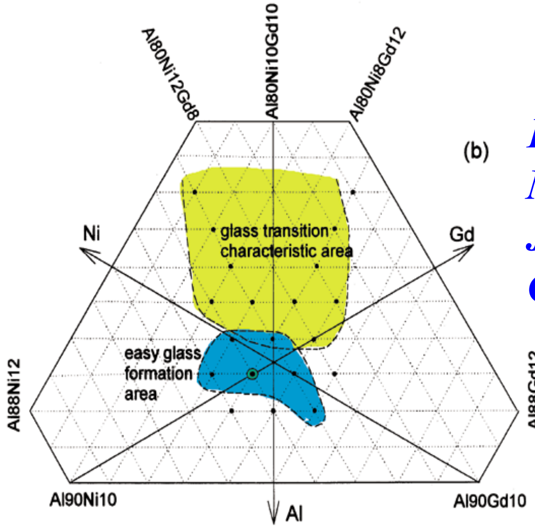
Tew et al.. J. Am. Chem. Soc. 1999, 121, 9852



Molecular dynamics simulations of fracture: Vashista et al (USC)

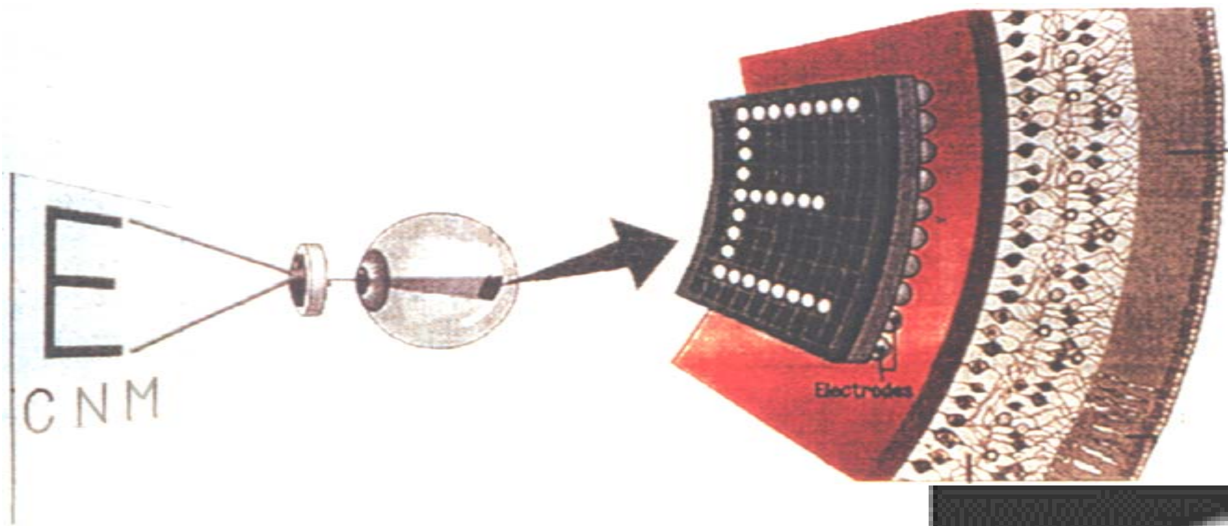


Wave function for a GaAs dot;
(A. Franceschetti and A. Zunger)

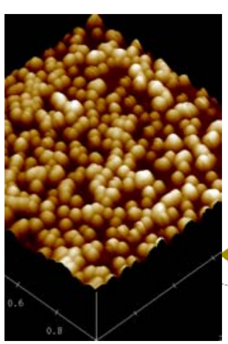


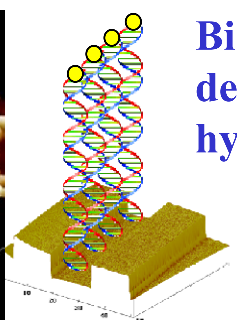
Formation of Metallic Glasses, J. Poon, G. Shiflet, UVa

The ***interface between nanomaterials and biological systems*** – enabling widespread improvements in human health.



Artificial retina with nanocrystalline diamond (USC, Argonne….)





Bioelectronic detection of DNA hybridization

20-40x increases in the ^{1}H MRI T_1 spin-lattice relaxivity rates for a Gd Trimetasphere wrt commercial agents (Omniscan, Magnevist)– VT, Luna, VCU

VCU C3B
Virginia Commonwealth University
Center for Bioelectronics, Biosensors and Biochips

OUTLINE

- What is Nanotechnology and Why Now?
- Nanotechnology in the Present
- Future Challenges and Opportunities in Nanotechnology: Towards Broad-Based Nanomanufacturing
- Future Technological Horizons

- ***Major Fields of Future Impact Include:***
  - ***Electronics / Computation***
  - ***Communications***
  - ***Data storage***
  - ***Energy storage / transmission / generation***
  - ***Health care***
  - ***Transportation***
  - ***Civil infrastructure,***
  - ***Military applications, national security***
  - ***Environment.***

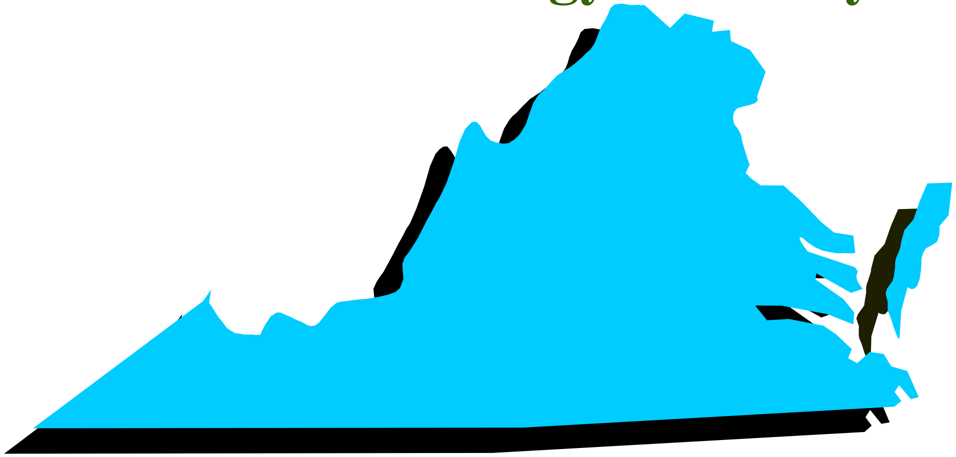
Emerging / Future Applications

- **Automotive and aeronautic industries:** *nanoparticle-reinforced materials for lighter, stronger bodies, nanoparticle-reinforced tires, self-cleaning and –repairing materials, electronics, collision avoidance*
- **Electronics and communications:** *extension of Moore's rule to thousands of times higher density, speed, lower power consumption and cost. Magnetic nanoparticle media*
- **Chemical materials:** *improved catalysts, smart magnetic fluids for vacuum seals / lubricants, self-cleaning and –repairing surfaces, adaptive surfaces*
- **Health care:** *nanostructured drugs, gene and drug delivery systems targeted to specific sites in the body, biocompatible replacements, self-diagnostics, bone/tissue regeneration and wound repair.*
- **Energy technologies:** *higher power density batteries, fuel cells, artificial photosynthesis, improved solar cells, improved fuel economy form lighter materials, improved electronics.*

- **Manufacturing:** *super-hard and –tough cutting tools, ultra-precision engineering based on nanoscale microscopies, atomic-scale manufacturing tools and processes, nanopowders, internal sensors for fault detection and repair, self-assembling materials*
- **Space exploration:** *lighter vehicles, improved energy generation, ultra-small robotic systems, in-flight sensing and repair capacity*
- **Environment:** *reduced pollution through catalysis, nanostructured traps for pollutant removal, improved recycling, selective membranes for water filtering, cleaner manufacturing processes*
- **National security:** *detectors and detoxifiers of biological and chemical agents, improved electronic and optical systems, radiation-protected systems, harder coatings and bodies, camouflage materials, improved textiles, self-repairing materials, in-battle medical care*

Education and Societal Outreach

- *How do these advances affect education at all levels - K-12, undergraduate, graduate, and beyond?*
- *How can we use nanoscience to educate and inspire society to be technologically literate?*
- *How can we encourage educational institutions to value and reward interdisciplinarity?*
- *How can we perform high-risk, high-cost research that will also benefit societies, or portions of societies, that cannot afford it?*



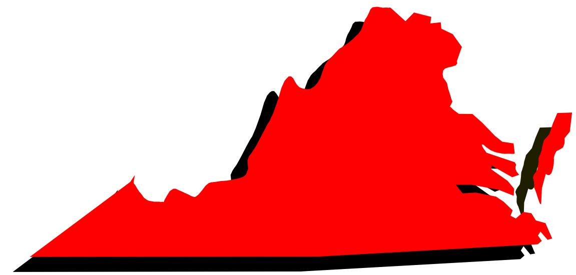
The Nano-Commonwealth

The Nano-Economy:

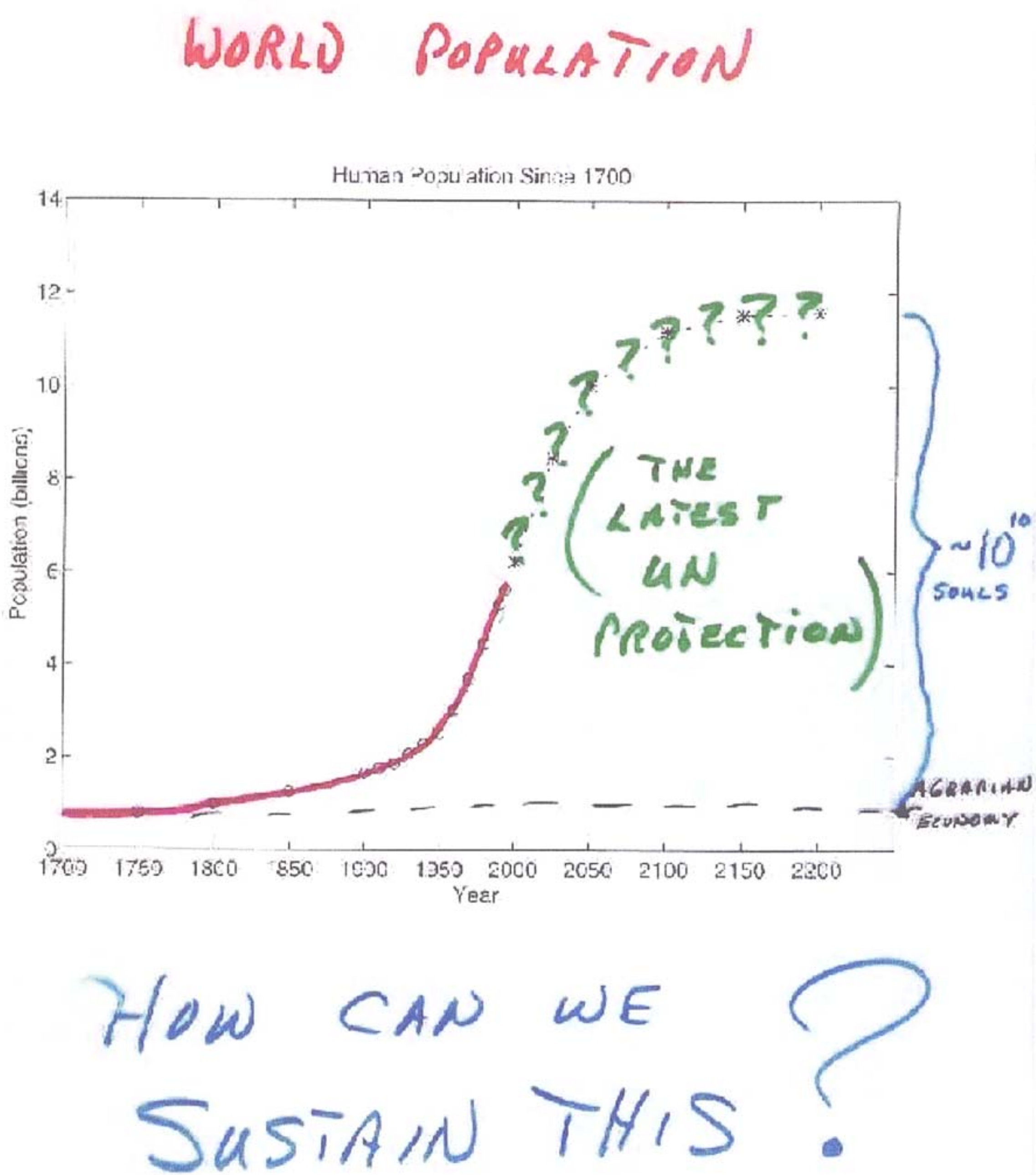
* Estimated world market by 2015: $1 trillion
* Projected U. S. jobs by 2015: 800,000 – 900,000

Opportunities in Virginia:

* Partnerships in Research, Manufacturing, Education Across the Commonwealth (Academic, Industry, Government Sectors)
* INanoVa (VNI), CIT, Research Consortia, CTRF
* Capitalize on Research Facilities, Expertise and People; Leading Educational Programs; Growing Nanomanufacturing Base



Where we should be



- **The Smalley Argument for Nano-technology!**